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COOLING TESTS OF AN AIR-COOLED ENGINE CYLINDER

WITH COPPER FINS ON THE BARREL

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WASHINGTON

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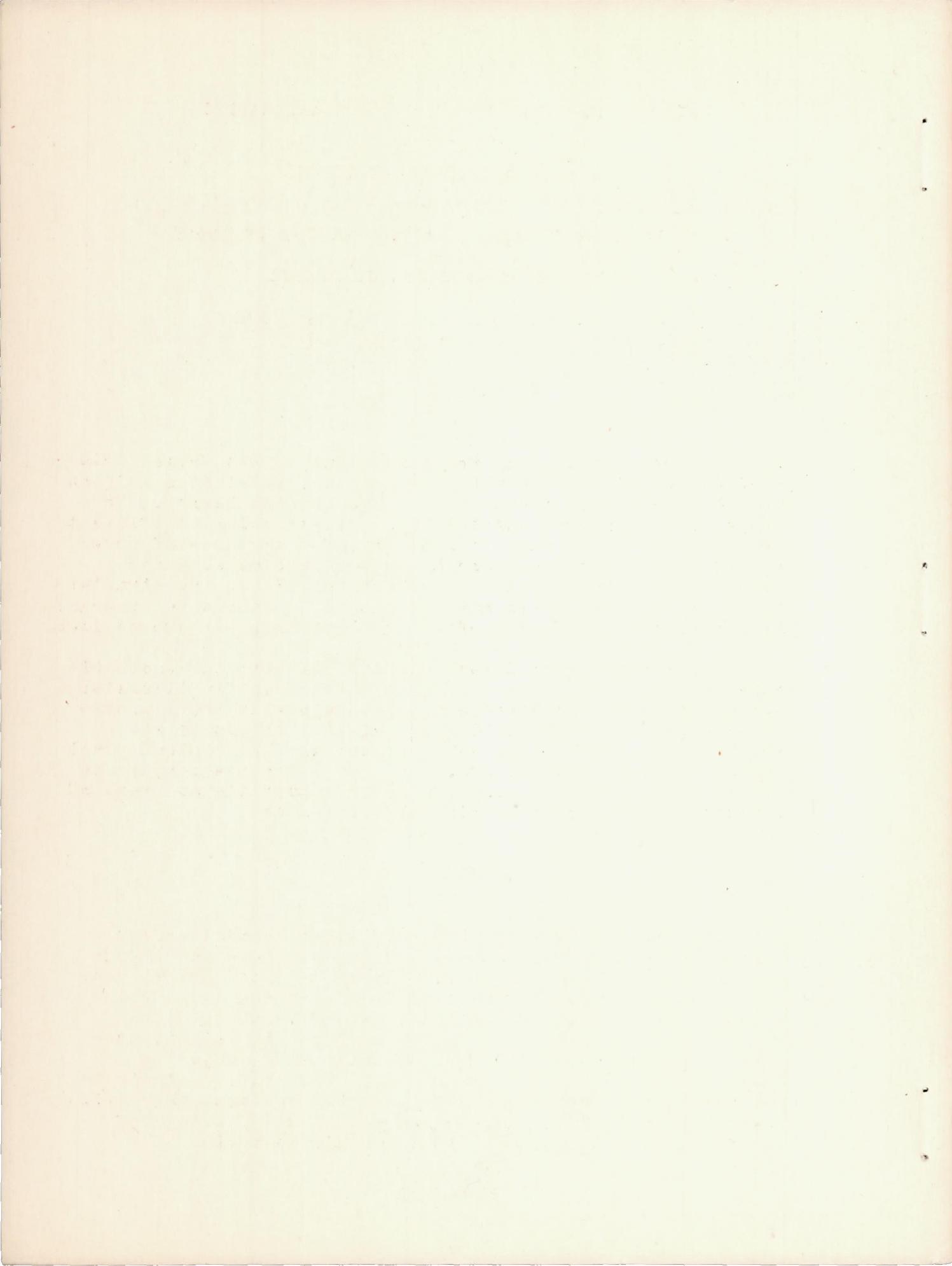
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SUMMARY

Comparative cooling tests were run on two Wright C9GC
(G-200) cylinders, one with the original steel fins and one
with 1-inch spiral copper fins brazed on the barrel. The
copper fins improved the over-all heat-transfer coefficient
from the barrel to the air 115 percent. At take-off power
the temperature of the barrel for the same cooling-air
pressure drop decreased from 297° F to 213° F. No structur-
al defect had developed after 60 hours of operation at brake
mean effective pressures of 45 to 258 pounds per square inch.

The improvements determined by test were in reasonable
agreement with the improvement computed from fin dimensions.
Computations were therefore made to determine the improve-
ment in cooling that could be obtained with copper and
aluminum fins having the same weights as the original steel
fins. In the ranges of practical fin sizes the copper and
aluminum fins were equally effective in cooling and were 80
percent better than the original steel fins.

INTRODUCTION

The problem of obtaining sufficient barrel cooling on
modern high-output air-cooled engines has been the object
of considerable investigation. Integral steel barrel fins
have apparently approached a limit of maximum cooling im-
posed by manufacturing difficulties. Previous studies
(reference 1) indicate that, for a given fin weight, con-
siderably more cooling may be obtained with copper or
aluminum fins than with steel fins. The chief obstacle to
the adoption of copper or aluminum fins has been the diffi-
culty of developing a completely satisfactory method of
attaching the fins to the steel cylinder barrels.

The most successful production method so far developed
for attaching fins has been the aluminum muff, which is an
aluminum cylinder with integral fins, machined from a single
aluminum billet. The muff is shrunk on the cylinder barrel.
Objections to the use of the muff are the cost of manu-
facture and the limitations of fin thickness and spacing
that can be machined on the muff.

Cylinder barrels having copper-plated steel fins have
been tried on an air-cooled diesel-engine cylinder. A
plating 0.008 inch thick on steel fins 0.043 inch thick re-
sulted in about 11-percent improvement in over-all heat
transfer. Copper plating, however, is limited in its range
of possible improvement by the relatively poor fin propor-
tions imposed by limitations in machining of the steel fins.
For a given cooling effectiveness the copper-plated fins
will weigh more than solid copper or aluminum fins.

Copper fins have been tested on barrels having electri-
cal heaters inside the bore. These tests showed copper fins
to be approximately as effective as aluminum fins on a
weight basis and both were considerably better than steel
fins. There are, however, several advantages that copper
fins have when compared with aluminum fins. The higher
thermal conductivity of copper permits the use of narrower
fins than can be used with aluminum fins for a required de-
gree of cooling, thereby interfering less with the air flow
to the second bank of cylinders in a two-row or inline
engine. Copper also has the advantage of being easily bonded
to steel by means of a brazing alloy, thereby offering the
possibility of a perfect bond. The type of finning described
in this report has the additional advantage of not requiring
a special thread belt on the barrel for attaching the cylin-
der head.

The object of this report is to show by power tests
the improvement that can be obtained in cooling by the re-
placement of steel fins by copper fins. Comparative cool-
ing tests were run on a standard Wright C9GC (G-200) cylin-
der on which the barrel fins had been replaced by a 1-inch
copper fin wound spirally eight turns per inch. Improve-
ments in cooling obtained in these tests were compared with
the improvements predicted by the use of calculations shown
in reference 2. An analysis was also made by computation
to compare the cooling obtainable with the original steel
fins and with copper and aluminum fins having the same
weights as the original steel fins.

A study was also made to determine the effect of barrel
cooling on piston temperatures. Obviously, as the barrel
cooling is increased, the temperature drop through the wall
increases and outside barrel temperatures are no longer a
satisfactory index of engine cooling. Thermocouples were
installed in the piston, and tests were run to determine
the effect of barrel cooling on piston temperatures.

The tests were conducted at Langley Memorial Aeronauti-
cal Laboratory during April and May 1942.

CYLINDER CONSTRUCTION

The copper-finned cylinder used in these tests con-
sisted of a copper-finned barrel screwed and shrunk into a
stock cylinder head. The barrel was a stock Wright nitrided
forging that was machined to accommodate the copper fins.
The copper finning was applied by Buensod-Stacey Air Con-
ditioning, Inc., in collaboration with the Induction Heating
Corporation and Handy & Harman.

The copper fins were applied in one continuous strip
that had been preformed to the proper shape. An adequate
length of strip was wrapped around the cylinder and pulled
tight. The assembly was fluxed and a silver solder wire
of the proper size and composition was laid between the
fins. The heating of the assembly was accomplished by
passing an induction heating head through the barrel at the
proper speed. The speed of the operation was just sufficient
to braze the spiral strip progressively to the barrel. The
entire brazing operation required approximately 5 minutes
and at no time was the nitrided barrel held at the brazing
temperature long enough to damage the nitrided case.

After the brazing operation, the fins were work-
hardened by a special tool. The finished barrel was sand-
blasted to remove the excess flux.

The completed barrel was assembled with the head in
the usual manner and the necessary machining operation re-
quired to complete the cylinder was performed.

APPARATUS AND METHODS

A standard Wright C9GC (G-200) cylinder with steel
fins shown in figure 1(b) was first set up on a single-
cylinder test unit and complete cooling tests were con-
ducted. The copper-finned cylinder (fig. 1(a)) was next
set up and comparative tests were run. A section of the
copper-finned cylinder showing the steel liner, the brazed
bond, and the fin is shown in figure 2. A comparison of
the dimensions of the original steel fins and the brazed
copper fin is given in the following table:

	Width (in.)	Thickness (in.)	Fins/inch	Axial length of finning (in.)
Original steel	0.65	0.025	$8\frac{1}{2}$	$5\frac{1}{2}$
Copper	1.0	.027	8	$5\frac{1}{4}$

In each case a stock Wright uniflow piston assembled
with stock rings was used. The piston used with the copper-
finned cylinder was equipped with thermocouples to measure
temperatures at the crown, the ring belt, and at a point
approximately midway in the skirt. The method of installa-
tion (reference 3) and the location of the piston thermo-
couples are shown in figures 3 and 4. The locations of
the cylinder-surface thermocouples are shown in figure 5.
The crankshaft used had a stroke of 7 inches, giving a dis-
placement of 206 cubic inches.

The principal components of the test apparatus are
shown diagrammatically in figure 6. The standard test-
engine equipment was used for measuring brake mean effec-
tive pressure, engine speed, fuel consumption, cylinder
temperatures, and fuel-air ratio. A separately driven
centrifugal blower supplied the cooling air. The quantity
of cooling air was measured by an 8-inch orifice at the
entrance of a 12-inch-diameter pipe. The pressure tap for
this orifice was 0.4 times the pipe diameter downstream,
as recommended in reference 4.

Tests of both the copper-finned cylinder and the
standard cylinder were conducted to determine the constants
used in equations for the average barrel and head tempera-
tures as functions of the fundamental engine and cooling
variables by the methods described in reference 5. Tests
were conducted in which each of the following was varied
in turn while the remaining factors were held constant:

(1) Brake mean effective pressure

(2) Mass flow of cooling air

(3) Fuel-air ratio, F/A

The tests covered the following range of conditions:

Brake mean effective pressure, pounds per
square inch 45-258

Cooling-air pressure drop across cylinder,
inches of water 1-20

Fuel-air ratio 0.055-0.105

The friction horsepower was determined by motoring
the engine at the test values of inlet-air pressure while
the oil pressure, the oil temperature, the speed, and the
cylinder temperatures were held at values as close as
possible to those obtained under power conditions.

The fuel used in the tests was Army-Navy Fuel Speci-
fication No. AN-VV-NF-781 having an octane number of 100.
For the more severe conditions, a sufficient amount of
lead to prevent audible knock was added.

METHOD OF COMPILING DATA

Although the cooling tests were run with conditions
as nearly the same on both cylinders as possible, it was
impossible to maintain constant cooling-air temperatures.
The cooling-air temperature varied from 79° F to 110° F,
making it necessary to apply some correction to the test
results before making a comparison. The test data were
therefore compiled in the manner outlined in reference 5.
The cooling characteristics of the cylinder barrel were
expressed in terms of the equation

$$\frac{T_b - T_a}{T_g - T_b} = K \frac{I^n}{(\Delta P \, \rho/\rho_0)^m} \tag{1}$$

where

T_b average outside barrel temperature, $^\circ F$

T_a cooling-air temperature, $^\circ F$

T_g effective temperature of gases in cylinder, $^\circ F$

K proportionality constant determined by test

I indicated horsepower

ΔP cooling-air pressure drop across cowling, inches water

ρ density of cooling air, taken as average of densities
of air approaching and leaving fins

ρ_o standard air density, taken as density at 29.92 inches
of mercury and 70° F

n experimentally determined exponent

m experimentally determined exponent

Other symbols used in this analysis are

H heat-transfer rate, Btu/hour

T_h average head temperature, $^\circ F$, taken as average reading
of head thermocouples indicated in figure 5

If T_g, K, n, and m are known, it is possible to
compute barrel temperatures for a wide variety of operating
conditions. From reference 5 it was found that, with a
spark advance of 23° B.T.C., and inlet-air temperature of
150° F, and a fuel-air ratio of 0.080, the values of T_g
should be

    Head   1200° F

    Barrel   630° F

Variations of T_g with fuel-air ratio were computed
from tests, as explained in reference 5. Constants for
the basic heat-transfer equations were determined. From
these equations the constants for the temperature correla-
tion formula (1) were determined. Similar equations were
developed for the rear spark plug and the exhaust valve
seat. The equations thus obtained were used to compute
the cylinder temperatures shown in later figures.

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tion formula (1) were determined. Similar equations were
developed for the rear spark plug and the exhaust valve
seat. The equations thus obtained were used to compute
the cylinder temperatures shown in later figures.

The method of correlating piston temperatures is explained in the discussion of results.

RESULTS AND DISCUSSION

Cylinder-Temperature Correlation

Figure 7 shows an example of uncorrected test data from the cylinders with the original steel fins and with the copper fins. The barrel with the copper fins was 60° F cooler at a power of 100 indicated horsepower. The cooling-air temperature, however, was 24° F hotter with the copper-finned cylinder. As a rough estimate, then, the reduction in barrel temperature resulting from the use of copper fins should be 84° F.

The various factors influencing cylinder temperatures were correlated in the form of curves shown in figures 8 through 12.

Figure 8 shows a comparison of the over-all coefficients of heat transmission for the original steel fins and the copper fins. The improvement resulting from the use of copper fins was 115 percent at 4 inches of water pressure drop. The theoretical increase in heat transfer as predicted by equations from reference 2 was 96 percent, a condition that shows that the improvements in cooling may be computed with reasonable accuracy.

The constants for the various cooling equations are obtained from the data shown in figures 8, 9, 10, 11, and 12. The general equation and constants are given below:

$$\frac{T_x - T_a}{T_g - T_x} = K \frac{(I/v)^n}{(\Delta P\rho/\rho_o)^m}$$

where

T_x temperature at a given point on cylinder, °F

I/v specific power output, indicated horsepower per cubic inch of displacement

ΔP cooling-air pressure drop across baffle, inches of water

The value of T_g is obtained from figure 9 and the values of K, m, and n are listed in the following table:

Location	K	n	m
Barrel, copper fins	0.770	0.59	0.31
Barrel, steel fins	1.560	.59	.27
Rear spark plug	1.085	.65	.27
Exhaust valve seat	1.110	.50	.22

Piston-Temperature Correlation

Figure 11 shows the results of tests to determine the effect of barrel temperature on piston temperature. Each curve represents data taken at constant power output. The barrel temperature was varied by changing the cooling-air pressure drop. It is shown that a slope of -0.5 may be used to represent the relation between $T_p - T_b$ and T_p for the range of temperatures involved. The relation between piston temperature and barrel temperature was therefore assumed to be

$$T_p - T_b = K + nT_p \qquad (2)$$

where n is slope of the curve at constant power representing the relation between $T_p - T_b$ and T_p

T_p piston-ring-belt temperature, ${}^oF$

T_b average barrel temperature, ${}^oF$

K an experimental function of power, inlet-air temperature, fuel-air ratio, spark advance, and compression ratio

Therefore $T_p - T_b = K - 0.5 T_p \qquad (3)$

For convenience the constant K is divided into two factors

$$T_p - T_b = fG - 0.5 T_p \qquad (4)$$

Factor G is the constant K when the fuel-air ratio is 0.080, the inlet-air temperature is 150° F, and the spark timing is 22° B.T.C. Variations in cooling resulting from variations in fuel-air ratio, inlet-air temperature, and spark timing are represented by f. Figure 12(b) shows the variation of fG with power computed from piston temperatures taken simultaneously with the barrel-cooling tests. The effect of fuel-air ratio is immediately apparent. From these curves the following values of f are obtained:

F/A	f
0.060	1.034
.080	1.000
.100	.910

The failure of a piston thermocouple at the termination of the barrel-cooling tests necessitated a disassembly of the engine. When the engine was reassembled the values of fG were slightly altered to about 30° F less at 150 indicated horsepower, representing a decrease in piston temperature of about 20° F at that power.

The relation between G and power can be represented by the equation

$$G = AI^r$$

where

A   proportionality factor

r   experimentally determined exponent, equal to slope of curves in figure 12(b)

G   correlation factor fG when F/A = 0.080

For the data of the barrel-cooling tests the constants were found to give the following equations

$$G = 55.1 \ (I^{0.44}) \tag{6}$$

$$G = 574 \ (I/v)^{0.44} \tag{7}$$

Substituting equation (7) in equation (4)

$$T_p - T_b = 574 \ (I/v)^{0.44} - 0.5 \ T_p$$

$$T_p = \frac{T_b + 574 \ (I/v)^{0.44}}{1.5} \tag{8}$$

Comparative Performance

The rated power of an engine using C9GC cylinders is approximately 0.7 indicated horsepower per cubic inch. Figure 13 shows that at this power output and a cooling-air pressure drop of 16 inches of water the average temperature is 213° F on the copper-finned barrel, as compared to 297° F on the steel-finned barrel. The corresponding piston-ring-belt temperatures are 467° F and 525° F. The piston temperature in this case changes 0.70° per degree of change in average barrel temperature.

Figure 13 also shows the decrease in required cooling-air pressure when the original steel fins are replaced by copper fins. For example, if it is desired to maintain a piston-ring-belt temperature of 525° F, the steel-finned barrel will require 16 inches of water, as compared with 1.2 inches of water for the copper-finned barrel.

Figure 14 extends the comparison of cylinder temperatures to higher and lower power outputs when the cooling-air pressure is 16 inches of water.

A comparison of the changes in piston and barrel temperatures as the result of improved fin design shows that the outside barrel temperature may be a poor criterion for barrel cooling. For example, at 0.7 indicated horsepower per cubic inch, the average temperature of the steel-finned barrel is 297° F, and of the piston, 525° F. If the power of the copper-finned cylinder were raised until the barrel temperature reached 297° F, the piston temperature would be well above 600° F and scuffing of the rings would be probable. It is therefore evident that the maximum outside barrel temperature should be reduced if the power is increased. Figure 15 shows the influence of power on the barrel temperature required to maintain a constant piston-ring-belt temperature of 525° F.

At the time of the preparation of this report, the copper-finned cylinder had completed 60 hours of operation with the brake mean effective pressure varying from 45 to 258 pounds per square inch. For the greater percentage of this time the engine was operated at an average brake mean effective pressure of 200 pounds per square inch. A close inspection of the finning did not reveal any structural weakness. The condition of the piston rings and the cylinder bore was particularly good.

Copper and Aluminum Fins Having the Same

Weights as the Original Steel Fins

The proportions of the copper fins used in these tests were selected solely for ease of fabrication and assembly. The best fin proportions will be considerably different from those selected for this test. These dimensions for a given cylinder are governed by many considerations that cannot be properly evaluated in this study. In some cases it is desired to use copper or aluminum fins having the same weight as the steel fins now used. A theoretical study is therefore given here to show the improvements in cooling that can be obtained from copper or aluminum fins having the same weights as the original steel fins on the Wright C9GC cylinder.

Figures 16 and 17 show the improvements in computed coefficients of over-all heat transfer, U, Btu/(sq in.)(°F)(hr), from the outside of the barrel to the air, when copper fins having the same weight as the original steel fins are used. The greatest improvement is 2.17 times the heat transfer from the original steel fins and is obtained with fins 1.4 inches wide and 0.0056 inch thick. Such thin fins might be considered to be impractical because they would have insufficient mechanical strength and because much thicker fins may be used with little sacrifice in cooling. At present the practical minimum fin thickness may be considered to be in the range from 0.010 inch to 0.020 inch thick. In this range the improvements in heat transfer with proper fin width and spacing are 1.8 to 2.1 times the heat transfer from the original fins and with no increase in fin weight.

Figure 18 shows the improvements obtainable from aluminum-muff fins having the same weights as the original steel fins. The range of practical fin dimensions in the

aluminum-muff design is restricted by limits imposed in machining the fins. With aluminum fins, as with copper fins, the fin thickness and spacing may vary considerably from optimum without serious loss in heat transfer.

Representative designs of copper and aluminum fins are compared below. In each case the dimensions were considered to be as near optimum as is practical to fabricate by modern methods of production:

Fins	Width (in.)	Thickness (in.)	Spacing (in.)	U/U_{steel}
Original steel	0.65	0.025	0.093	1.00
Copper	1.10	.018	.155	1.85
Aluminum	1.10	.025	.106	1.78

Roughly, the copper and aluminum fins give the same cooling, which is about 1.8 times the cooling of steel fins, provided that the weights of the fins are equal.

CONCLUSIONS

From the comparative cooling tests on a standard cylinder with steel fins on the barrel and on a cylinder with copper fins on the barrel, it may be concluded that:

1. The 1-inch copper fins had a 115-percent greater over-all coefficient of heat transfer than the original steel fins. This improvement resulted in a reduction of average barrel temperature at rated maximum continuous power from 297° F to 213° F.

2. The improvement to be obtained with better fins may be computed with reasonable accuracy by the use of the method shown in reference 2.

3. Computations show that, in the range of practical fin dimensions, copper fins having the same weight as the original steel fins will give at least 1.8 times the over-all heat transfer of the original steel fins.

4.   In the range of practical fin dimensions, copper-
and aluminum-muff fins having the same weights will give
approximately the same over-all heat transfer.

5.   The piston-ring-belt temperature is believed to
be a more accurate criterion than barrel temperatures for
required engine cooling.

6.   For equal piston-ring-belt temperatures, a lower
maximum permissible barrel temperature will be required
when improved cylinder barrel cooling is provided.

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       National Advisory Committee for Aeronautics,
            Langley Field, Va.

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    NACA Rep. No. 683, 1940.
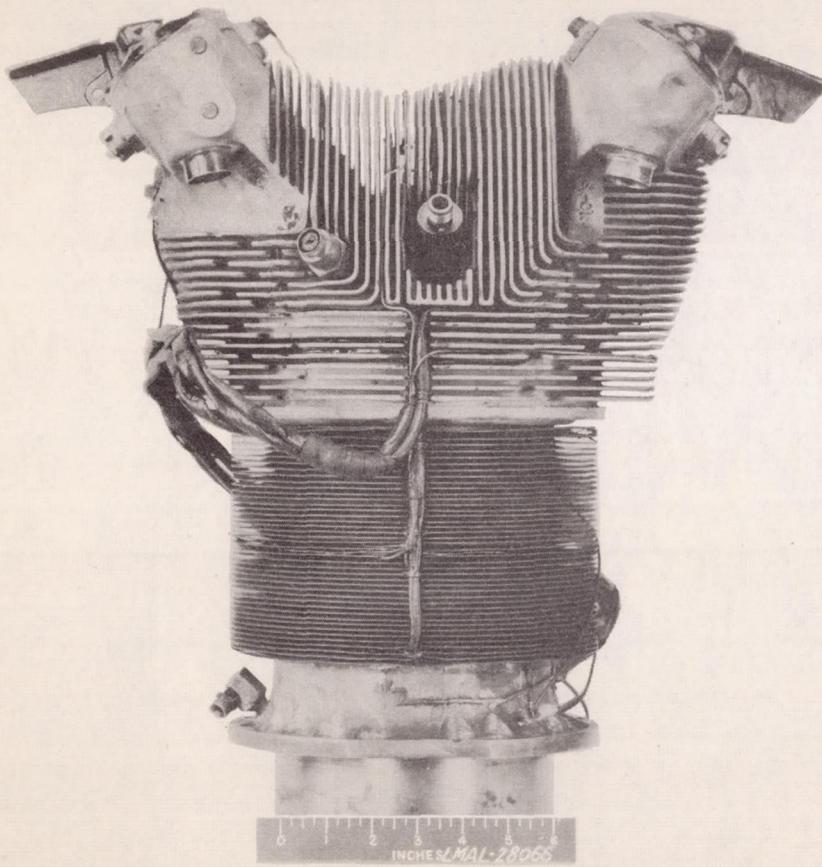
(a) Copper-finned barrel.
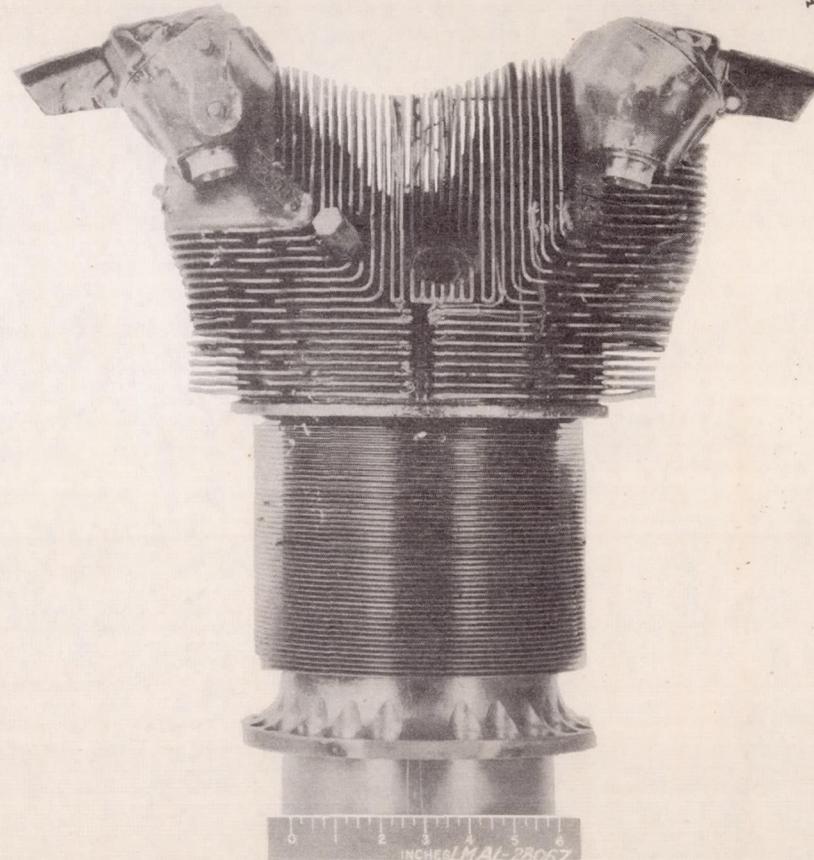
(b) Standard C9GC barrel.

Figure 1.- Photograph of Wright C9GC cylinders with original steel fins and with 1-inch spiral copper fins.

Fig. 1

Fig. 2

#36
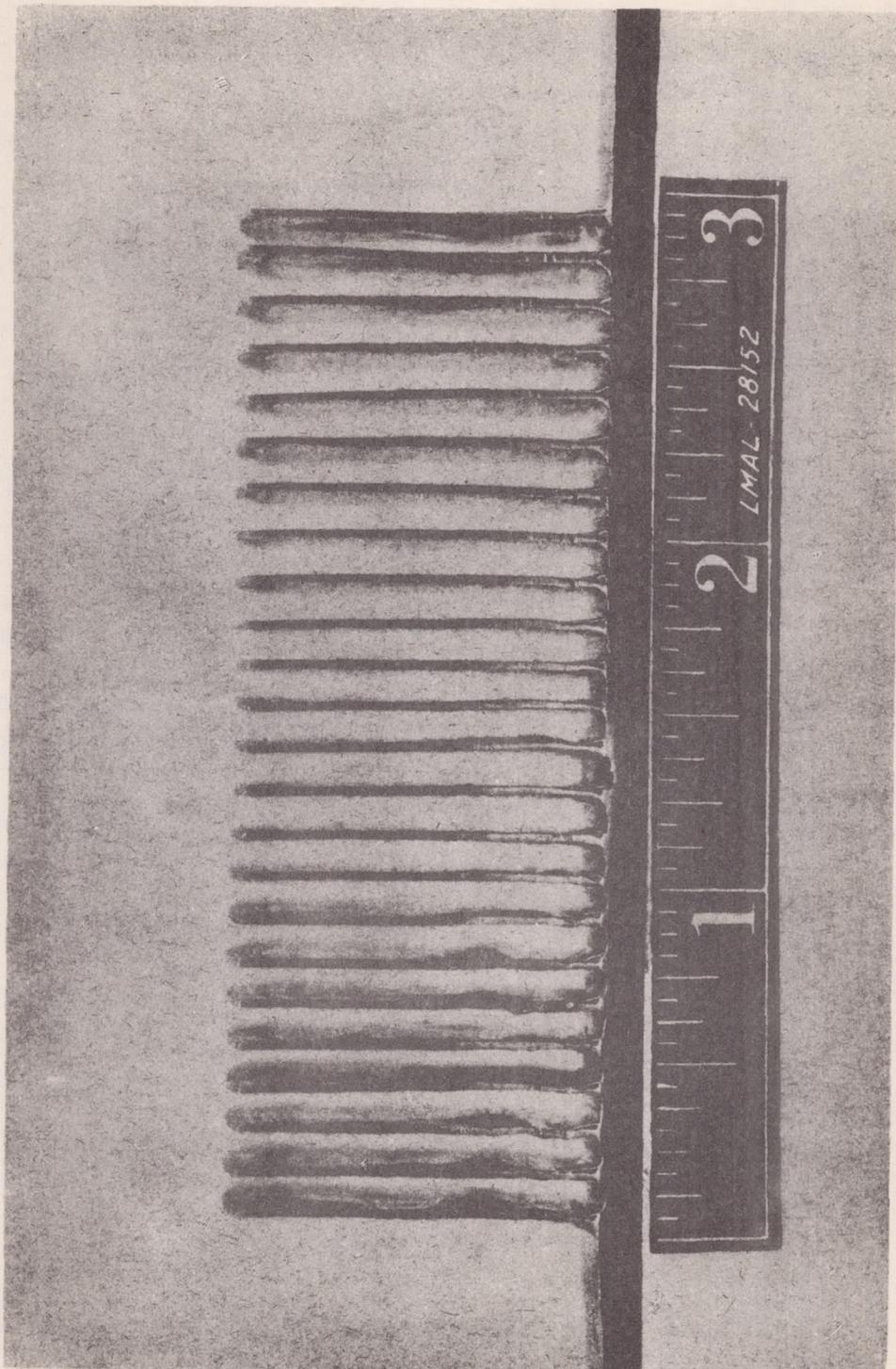
Figure 2.- Photograph of a cross section of the copper fins.
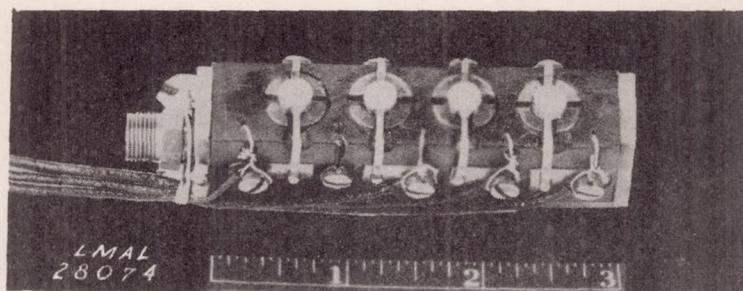
(a)   Plunger block with contacts.
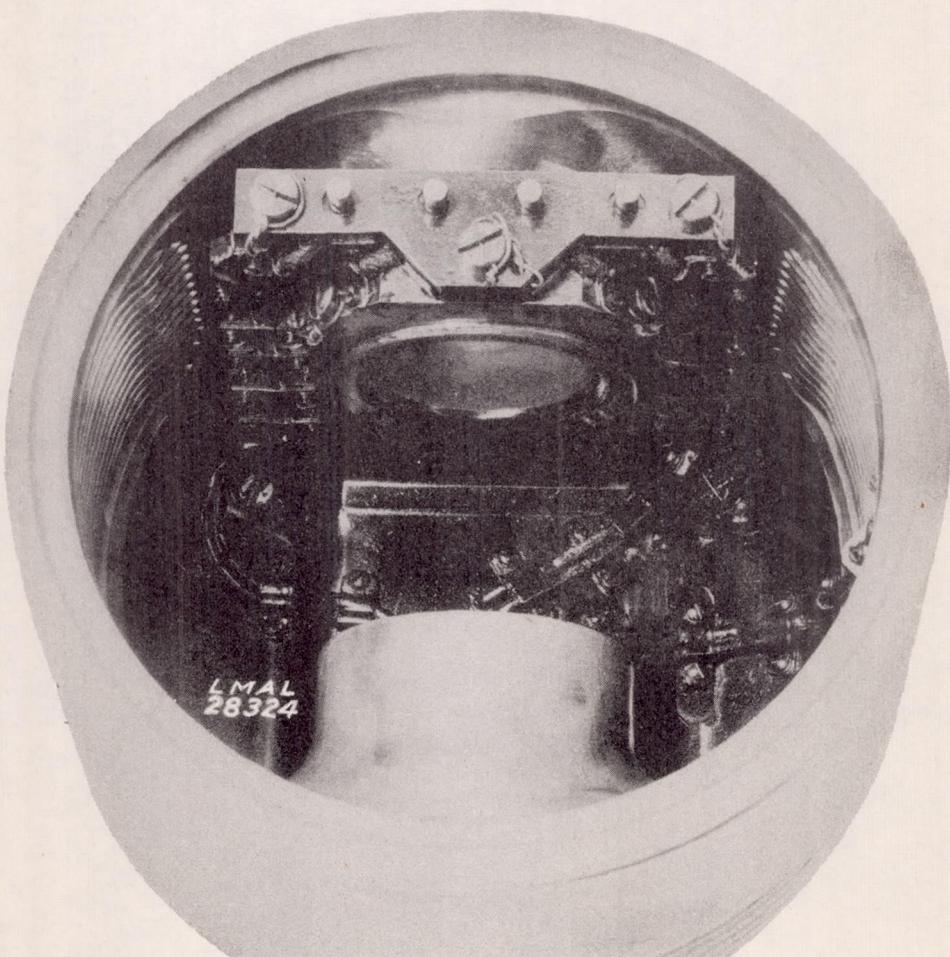
(b)   Piston with thermocouple installation and contacts.

Figure 3. - Piston-thermocouple installation.
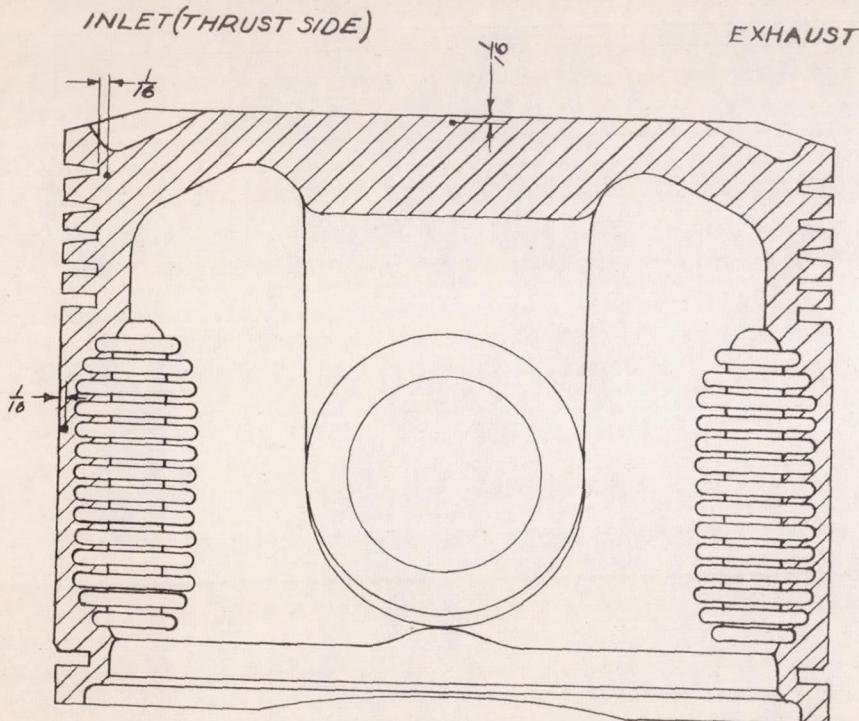
INLET (THRUST SIDE)   EXHAUST

$\frac{1}{16}$

$\frac{1}{16}$

$\frac{1}{16}$

FIGURE 4. — LOCATION OF PISTON THERMOCOUPLES.

o Copper fins

+ Original steel fins

Piston-ring-belt temperature

Average barrel temperature

Cooling-air temperature

Temperature, °F

600

400

300

200

100

80

60

30   40   60 80 100   150 200

ihp
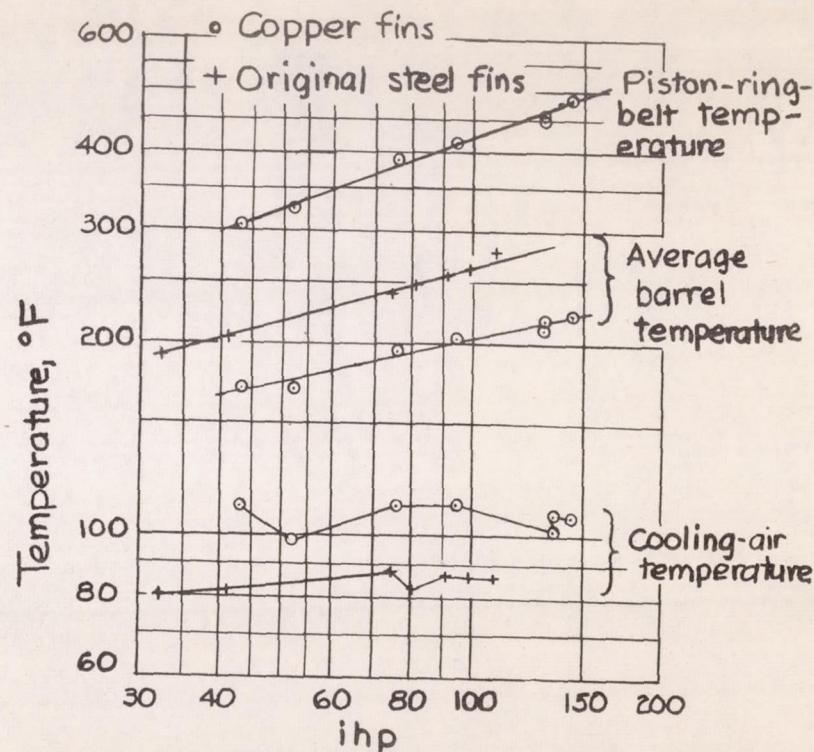
Figure 7. — Examples of uncorrected
test data. Inlet-air temperature, 150°F;
engine speed, 2000 rpm; cooling-air
pressure drop, 16 inches of water; fuel-
air ratio, 0.080.
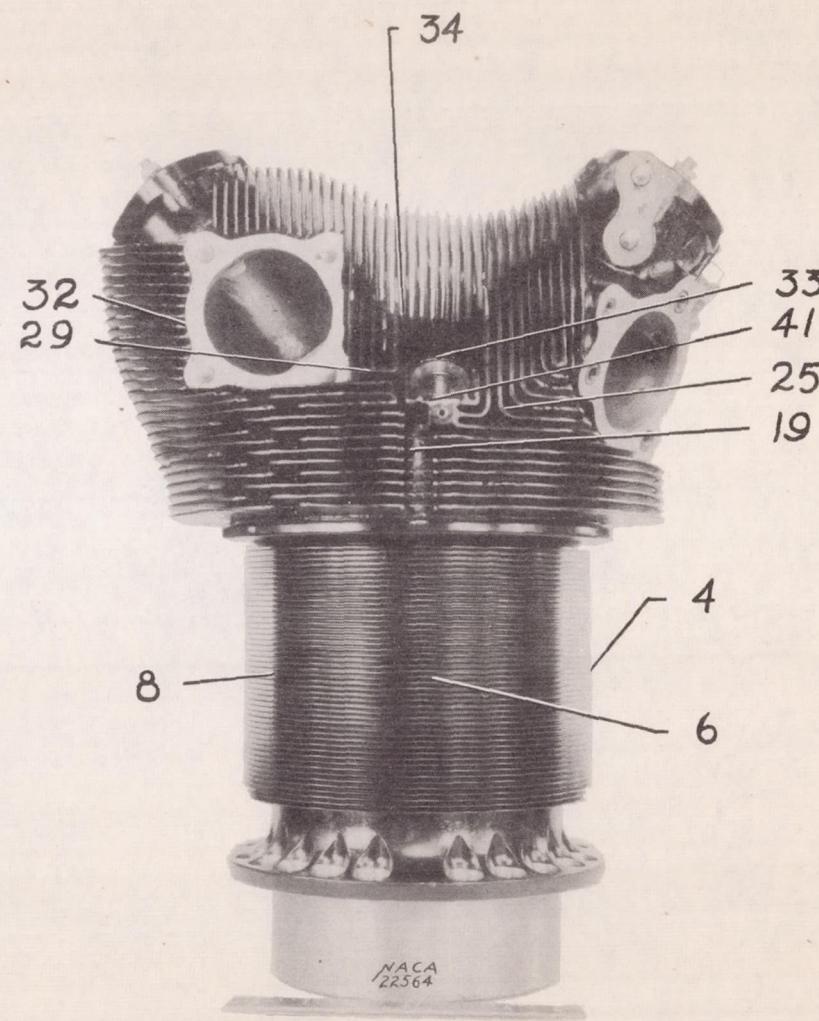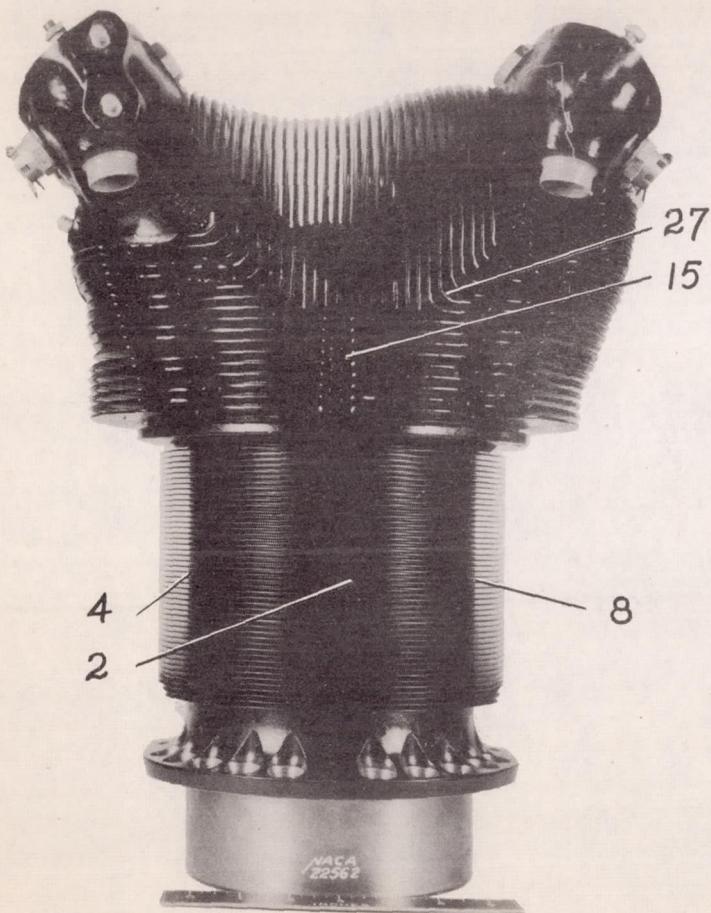
Figure 5. - Location of surface thermocouples.

Fig. 5

Orifice

Static-pressure manometer

Thermometer

Carburetor

Cowling

Thermometer

Light-beam galv.

Potentiometer

Selector switch

Distributor

Surge tank

Mixing valve

Air heaters

Orifice

Press regulator

Line from blower

Thermometer

Two-way valve

a, Orifice differential
b, Inlet cooling-air pressure
c, Manifold pressure
d, Surge-tank pressure
e, Orifice differential
f, Orifice total pressure

Cooling-air blower

Engine

Dynamometer

Figure 6.-Diagrammatic layout of equipment.

Fig. 6
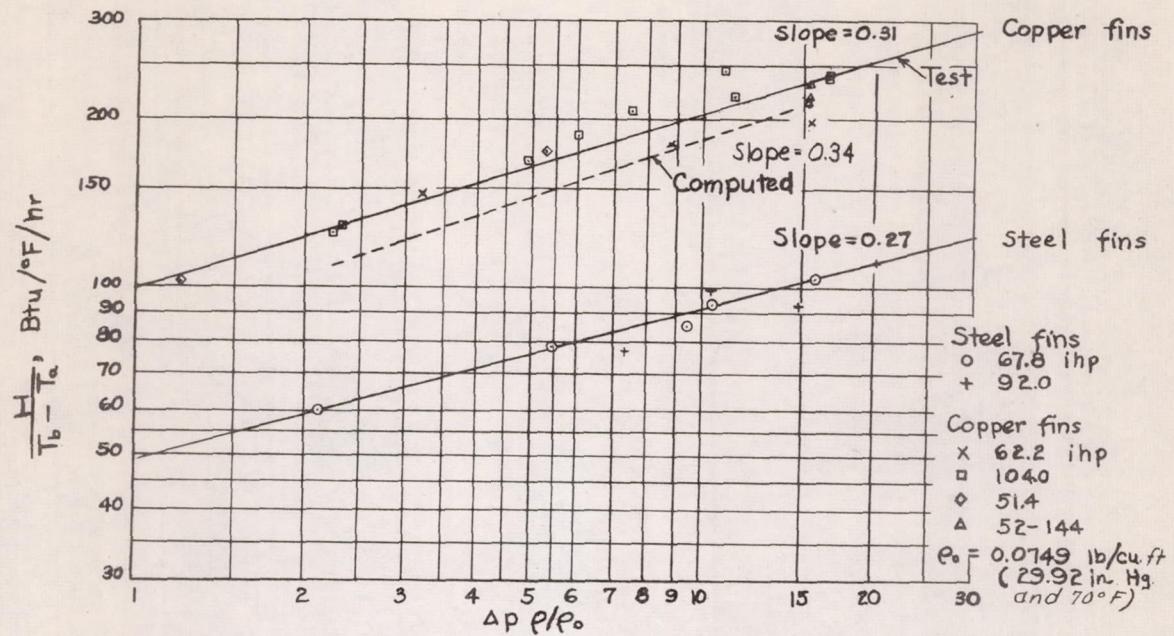
Figure 8.- Comparison of heat-transfer characteristics of original steel fins and copper fins. Wright C9GC cylinder.
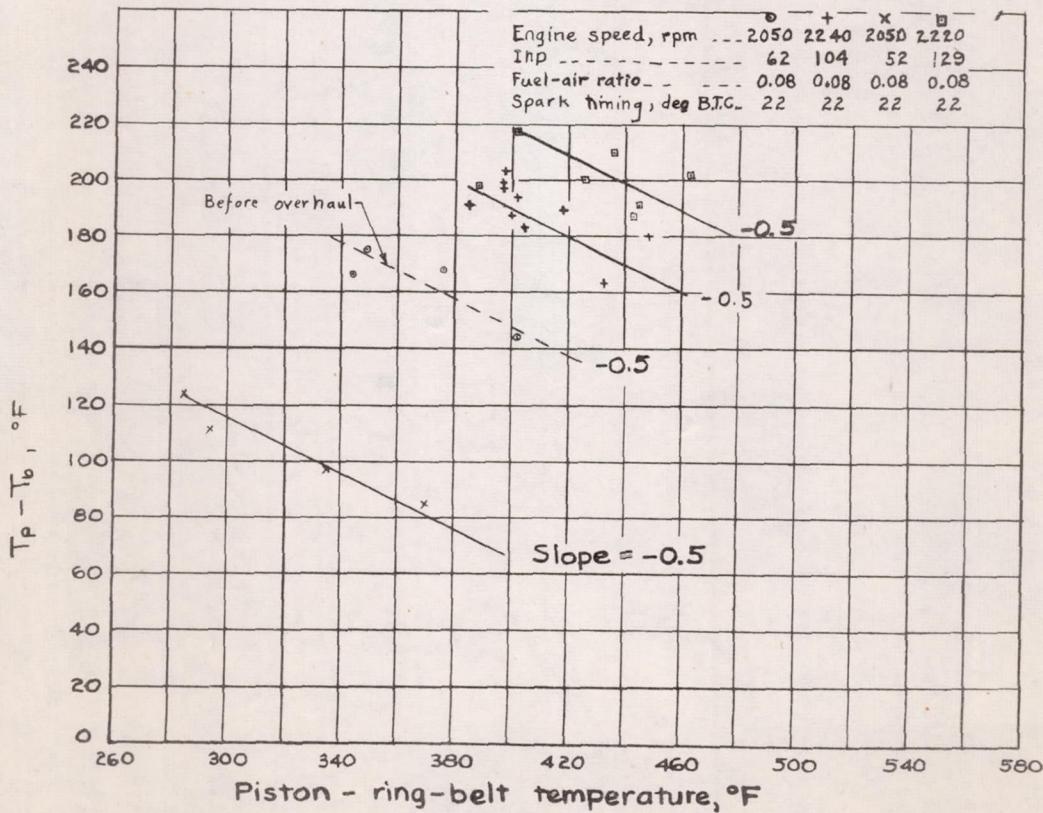
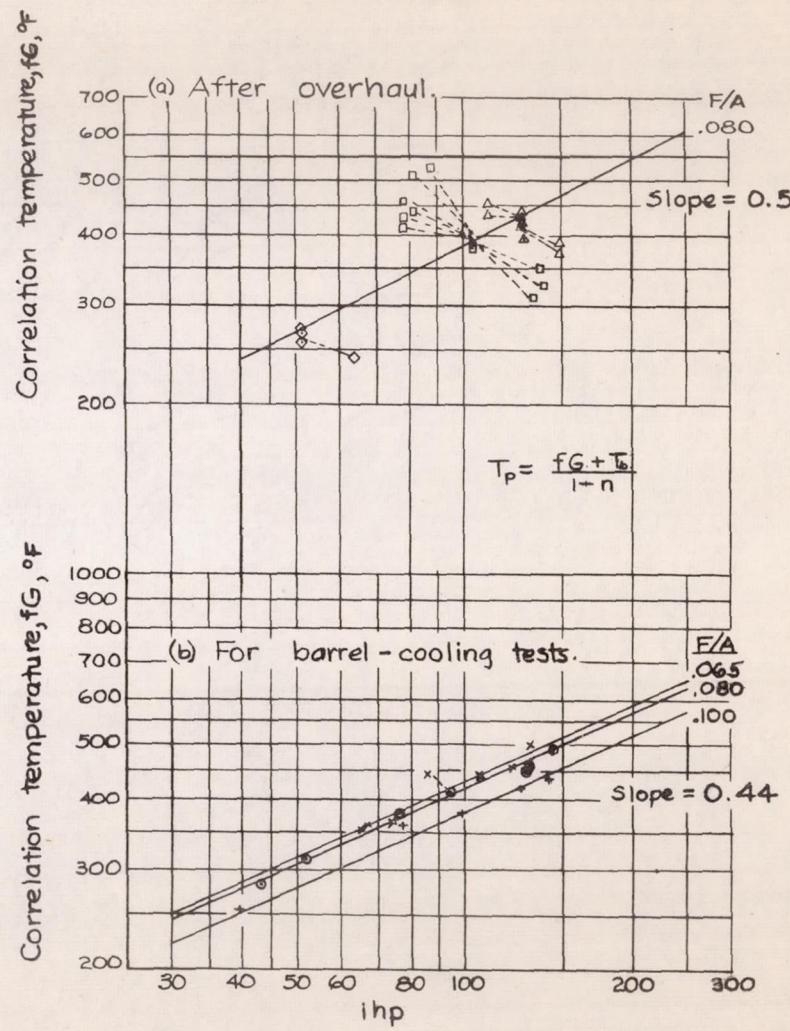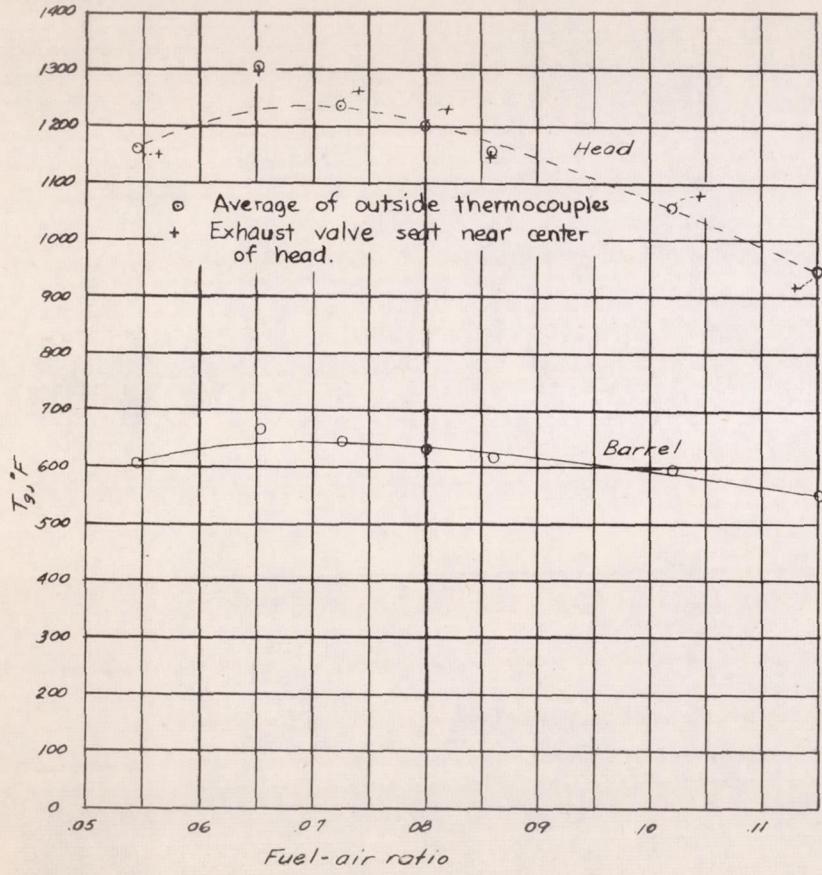Figure 11 - Influence of barrel temperature on piston temperature.

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Figure 9. (left chart)

o Average of outside thermocouples
+ Exhaust valve seat near center of head.

Head

Barrel

T_g, °F

Fuel-air ratio

Figure 9.— Effect of mixture ratio on T_g

Figure 12 (right charts)

Correlation temperature, t_G, °F

(a) After overhaul.

F/A .080

Slope = 0.51

$$T_P = \frac{fG + T_0}{1 + n}$$

Correlation temperature, t_G, °F

(b) For barrel-cooling tests.

F/A .065 .080 .100

Slope = 0.44

ihp

Figure 12.— Piston-temperature correlation. C9GC cylinder.

(a) Heat transfer from cylinder head to air.

(b) Correlation of temperature of the rear spark-plug bushing. $\Delta p\,\rho/\rho_0$, 15.3 in. water.

(c) Influence of horsepower on heat transfer to cylinder barrel

Standard cylinder
- o F/A = 0.080
- +   0.100
- x   0.065

Copper-finned cylinder
- □ F/A = 0.080
- ◇   0.100
- △   0.065
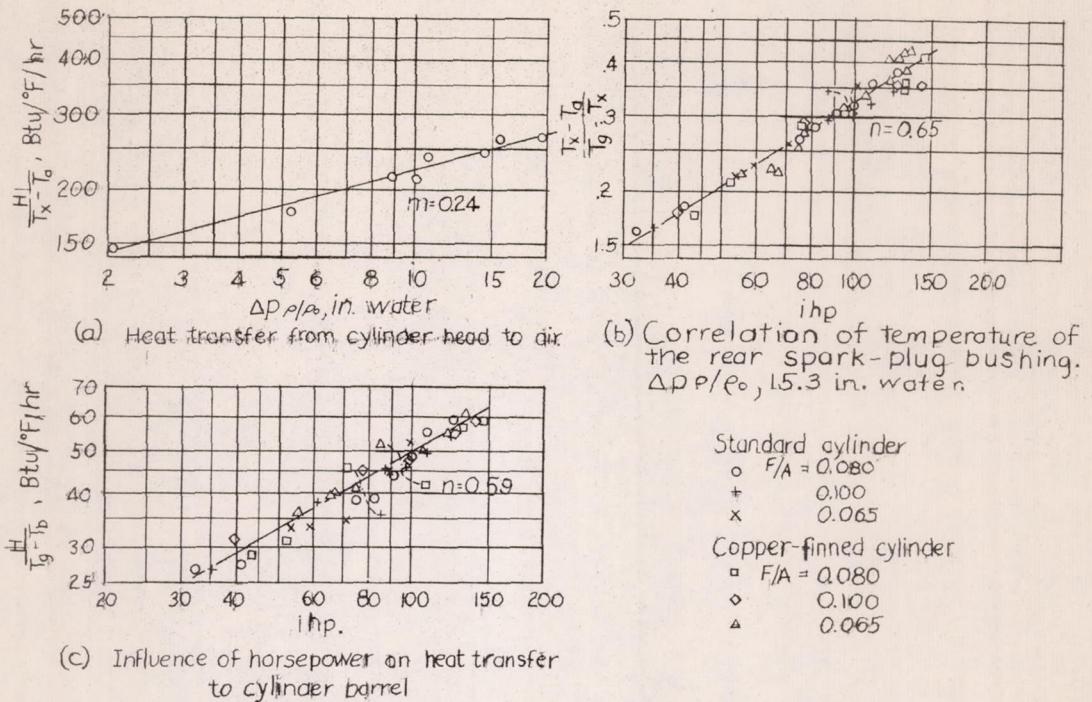
Figure 10.- Correlation of cylinder temperatures.
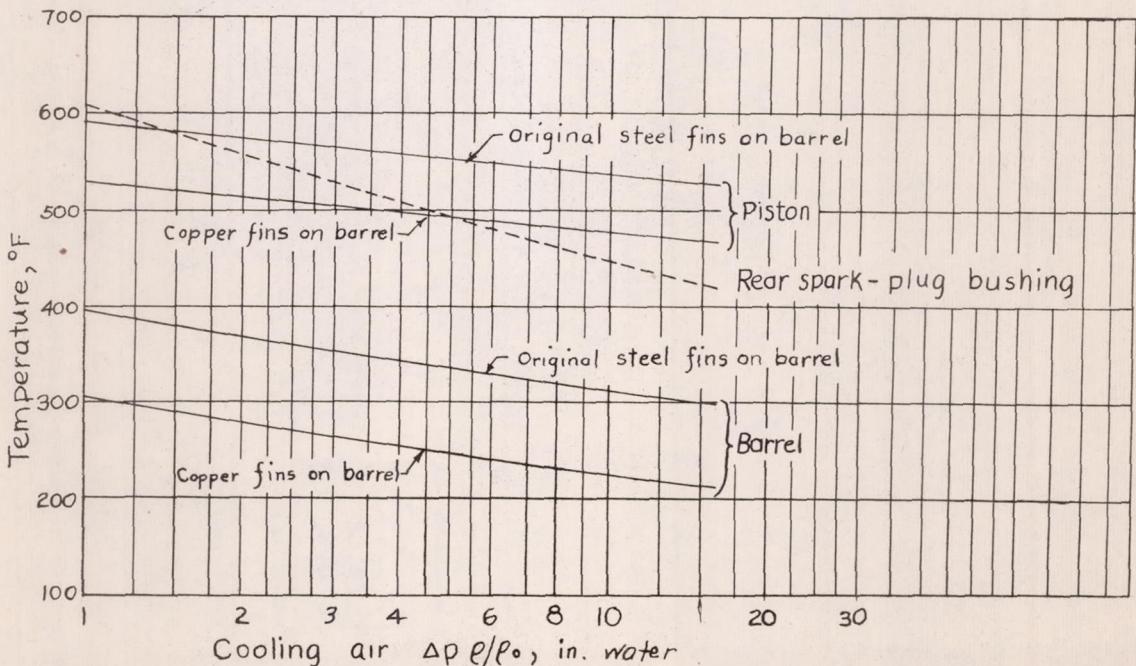
Figure 13.- Effect of cooling-air pressure drop on cylinder temperatures. Indicated horsepower per cubic inch, 0.070; cooling-air temperature, 100°F; inlet-air temperature, 100°F; fuel-air ratio, 0.080.

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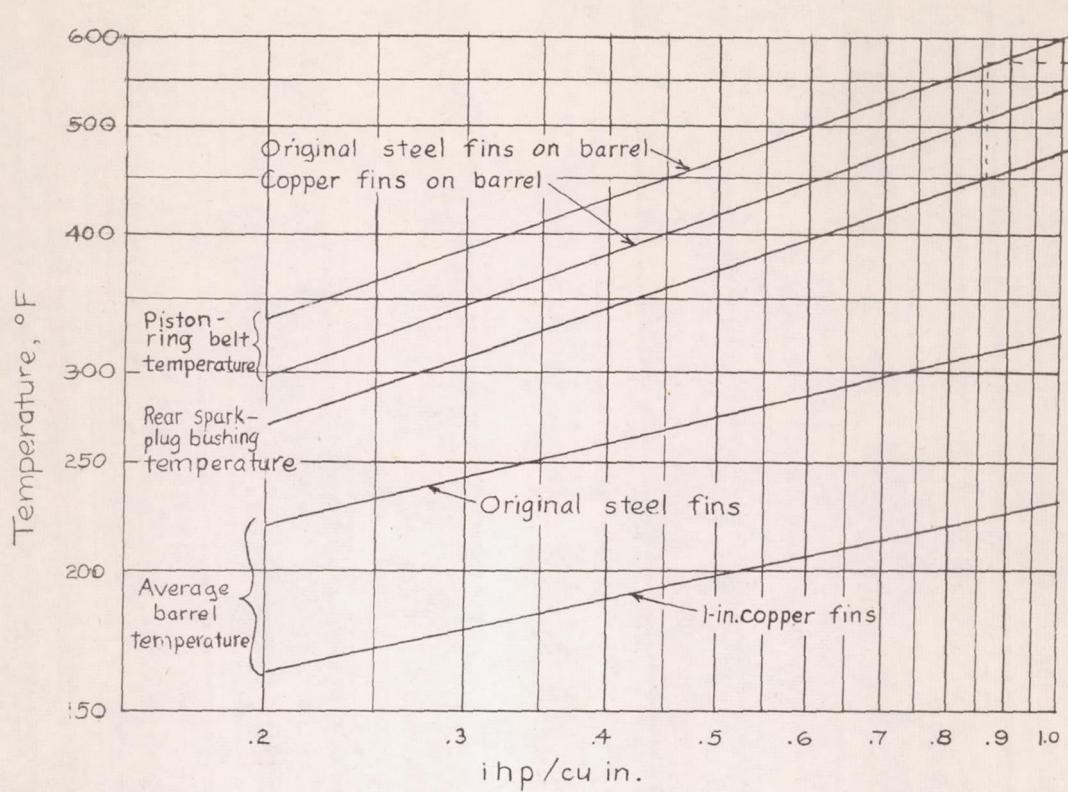
Figure 14.- Effect of improved barrel cooling on cylinder temperatures.
Cooling-air temperature, 100°F; inlet-air temperature, 150°F;
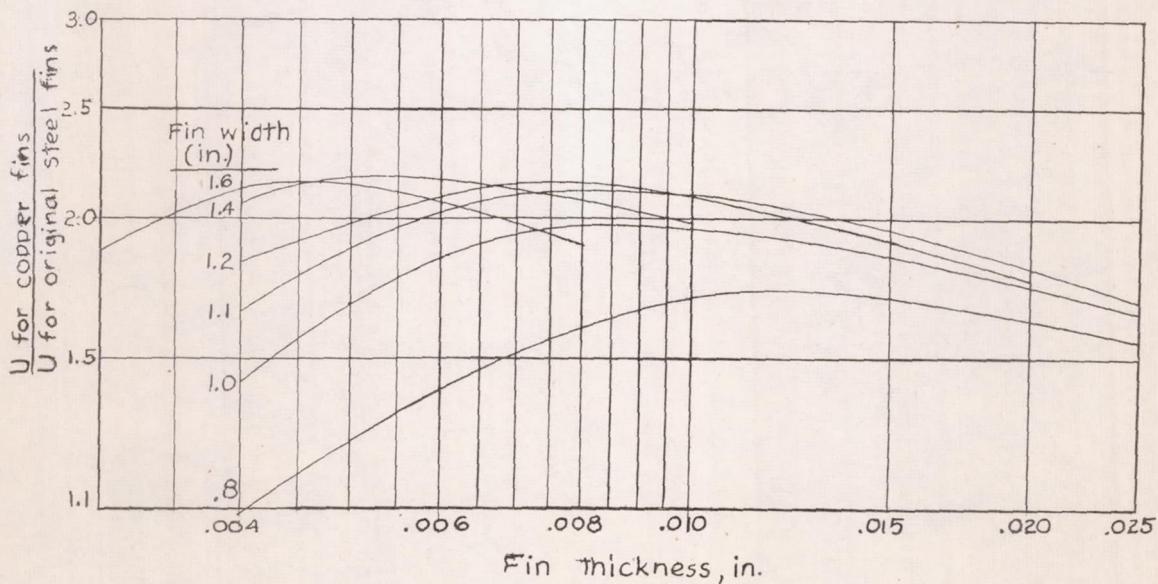fuel-air ratio, 0.08; Δp ρ/ρ₀, 16.0 in. water.

Figure 16.- Influence of fin dimensions on the heat-
transfer coefficient of copper fins having the
same weight as the original steel fins on a
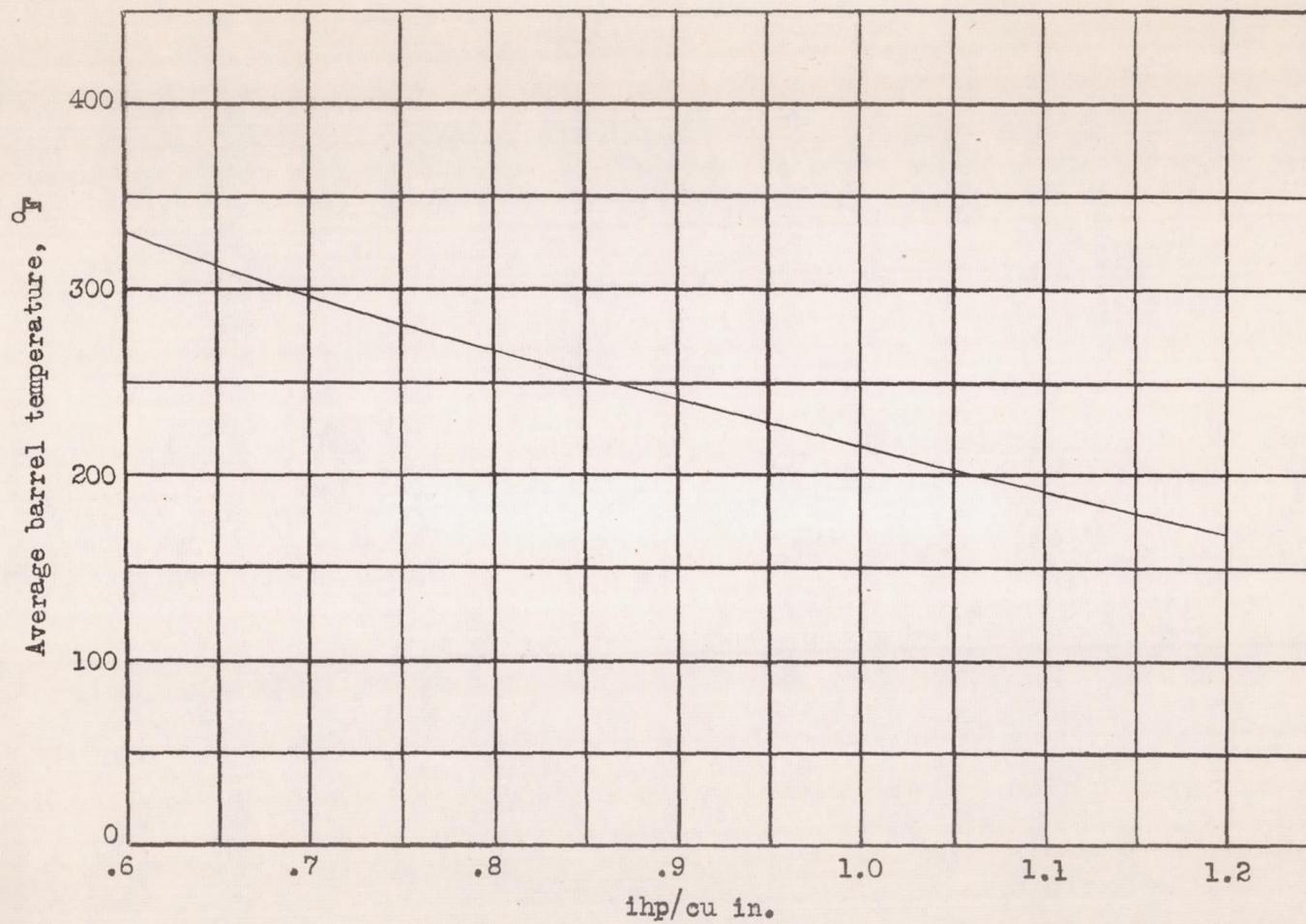C9GC cylinder barrel.

Figure 15.- Average barrel temperature required to maintain a piston-ring-belt temperature of 525° F. Inlet-air temperature, 150° F; fuel-air ratio, 0.080.
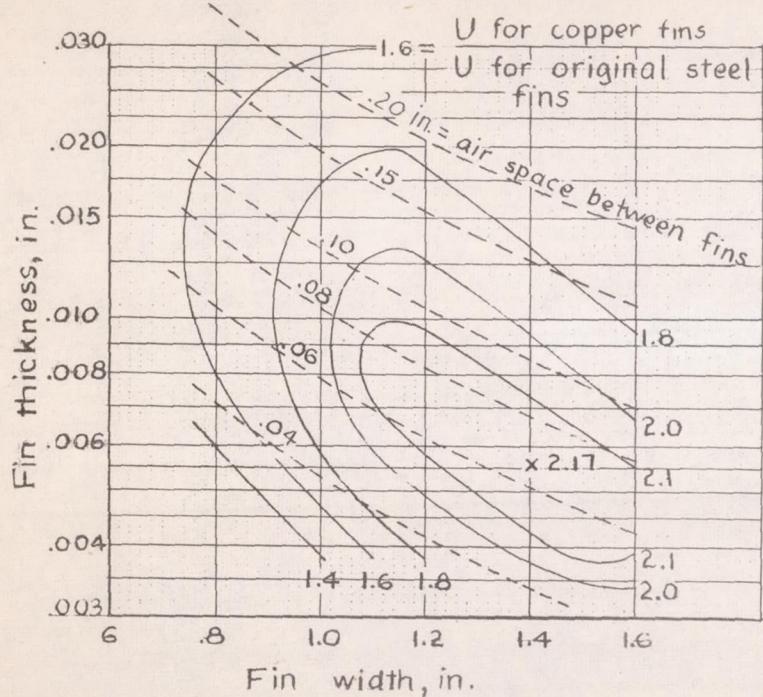
Fig. 15

Figure 17.- Sizes of copper fins having the same weight as the original steel fins on a Wright C9GC cylinder barrel.
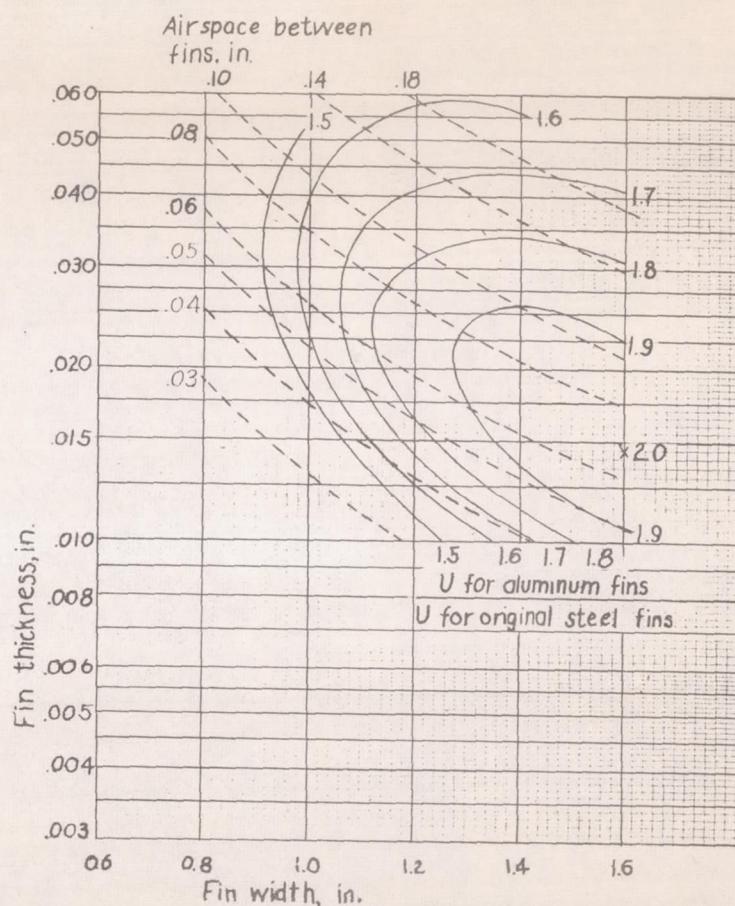

Figure 18.- Sizes of aluminum-muff fins having the same weight as the original steel fins on a Wright C9GC cylinder barrel. Sleeve of muff, 3/32 inches thick; weight includes sleeve.